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Mass flow calculation method for a thermal biosludge drier

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Sludge generated at waste water treatment plant has to be disposed of. As generating site and disposal site are not necessarily in close proximity, reducing the sludge becomes pivotal to avoid unwanted transportation costs or improving the heat value of the sludge by drying. The initiatory motivation for this thesis project was the commissioning of a thermal biosludge drier taken to use for drying biosludge before incineration. Previously the sludge had been transported over 100km from the site for composting.

The implemented thermal sludge drier was lacking a mass flow calculation method that was vital to provide information of the amount of energy in the fuel incinerated in fluidized sand bed boiler as the sludge was a secondary fuel. This information was important as biosludge generated at paper mill is considered as a by-product and a renewable energy source and is there for subject to feed tariff in electricity generation and heat premium in heat production.

This thesis project details a mass flow calculation method where the mass flow is derived from the sludge flows to centrifuges located prior in the process to the thermal drier.

Keywords	biosludge, biological sludge, excess sludge, sludge treatment, thermal sludge treatment, sludge incineration

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Jätevesiasemalla muodostunut liete täytyy loppusijoittaa. Lietteen syntypaikka ja loppusijoitus paikka eivät välttämättä ole toistensa välittömässä läheisyydessä ja tällöin loppusijoitettavan aineen määrän vähentäminen tulee erittäin tärkeäksi kuljetuskulujen hallitsemiseksi tai lämpöarvon nostamiseksi ennen polttoa lietettä kuivaamalla. Tämän insinöörityön taustalla on yrityksessä käyttöön otettu terminen bioliettееn kuivain. Ennen kuivaimen käyttöön ottoa liete kuljetettiin yli 100km päähän kompostoitavaksi.

Käyttöön otetussa termisessä kuivaimessa ei ollut minkäänlaista massavirran mittausta polttoon menevän lietteen määrän määrittämiselle. Tämä tieto on erittäin tärkeä, koska paperitehtailla syntyvä liete määritetään metsäteollisuuden sivutuotteeksi sekä uusituvaksi biopolttoaineeksi ja on näin ollen sen käytöstä maksetaan syöttötariffia sähköntuotannossa ja lämpöpreemiota lämmöntuotannossa.

Tässä insinöörityössä poltetun lietteen massavirta määritetään prosessissa ennen termistä kuivausta olevien lietelinkojen massavirtojen avulla.

Avainsanat	bioliete, biologinen liete, ylijäämäliete lietteen käsittely, terminen lietteen käsittely, lietteen poltto

Dedication

For Neea, you made me realize how fast time goes by.

Contents

1 Introduction

Sappi Kirkniemi is a paper mill located in Southern Finland by the Lake Lohja. The mill is part of Sappi Fine Paper Europe. The mill has three paper machines producing coated papers for heat set web offset printing to customers around the world. The mill has an annual capacity of 735000 tons and employs approximately 600 people. [1]

By the paper machines there are two ground wood plants producing ground wood pulp (GWP) and pressurized ground wood pulp (PGWP) and a chip refinery producing refined mechanical pulp (RMP). The combined capacity of these mechanical pulp plants is 330000 tons per year. Chemical pulp, pigments and other materials are transported to the site by rail and roads. [1]

The mill also has its own power plant and wastewater treatment plant. The power plant uses natural gas, wood waste and the sludge generated in the wastewater treatment plant as a fuel. The wastewater treatment plant treats all the effluent from the paper machines and utilities, totaling 6 477 000 m^3 of effluent on 2012. From this wastewater sludge is collected and incinerated at the power plant. [1]

Early 2012 the main part of Sludge2Energy project was completed and thermal biosludge drier was taken to use at the wastewater treatment plant, and since then the biosludge from the active sludge process has been dried and incinerated in the power plant. As different fuels are treated and taxed differently by the authorities it became important to known the amount of biosludge incinerated. The aim of this thesis work was to create a method of mass flow calculation for the biosludge drier.

At the starting point no measurement system had been designed for the biosludge drier even though sludge was already incinerated at the mill's power plant. Meeting was held at June 2012 to address the problem. At the meeting two alternative ways for the measurement came to the table. Green light was given for a calculation system that was completely based on online flow and consistency meters. Because of serious measurement errors, plans had to be changed later.

This thesis will consist of a detailed process description of the wastewater treatment plant and the biofuel boiler (K2) covering those parts relevant for the biosludge incineration. Also it review generally sludge treatment processes used commonly and explains related standards and legislation issues relevant to the topic.

2 Sappi Limited

Sappi Limited is global paper and pulp company group. It is operating in over 20 countries and has about 14 000 employees globally. It has manufacturing operations in three continents with a combined capacity of 6 million tons of paper and 3 million tons of pulp. The company is divided geographically to Sappi Fine Paper Europe, Sappi Fine Paper North America, Sappi Southern Africa and Sappi Trading. The group headquarters is located in Johannesburg, South Africa. [2]

Sappi Fine Paper Europe (SFPE) is the biggest division of Sappi Limited comprising 53% of the group sales. SFPE has eight mills and 20 sales offices around Europe employing more than 6000 people. This thesis was completed for SFPE's Kirkniemi mill. Figure 1 shows Sappi Kirkniemi in numbers. [2]

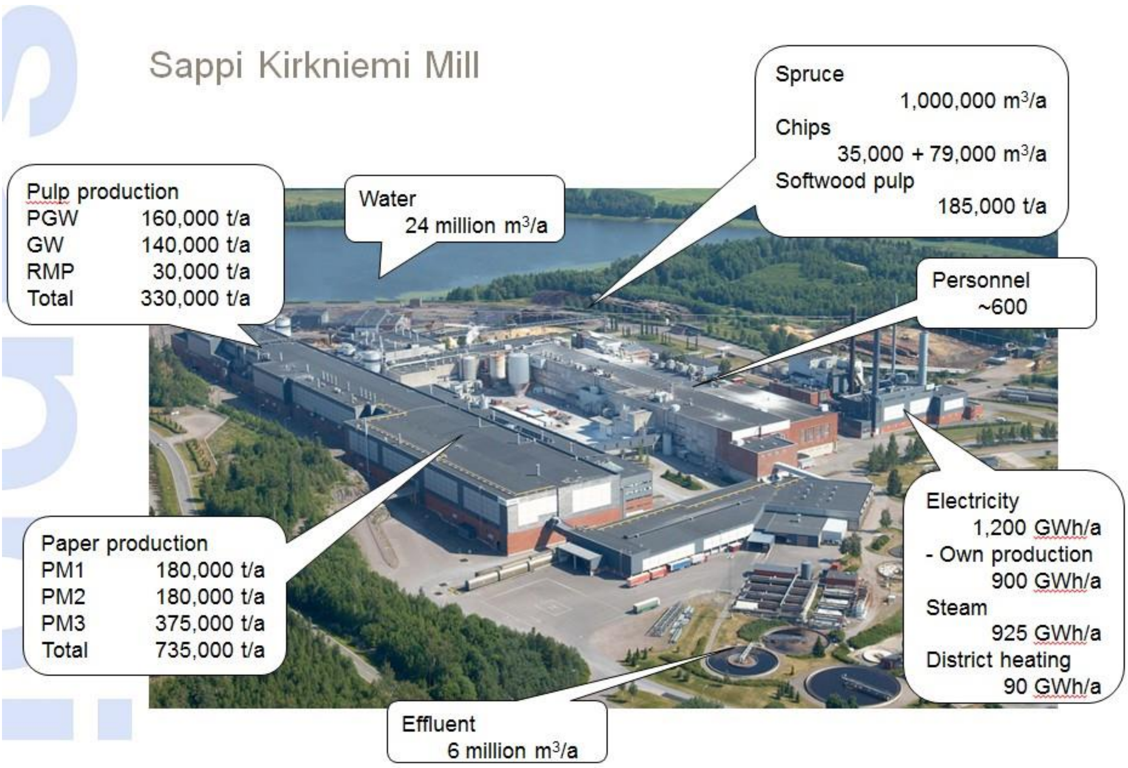

Figure 1: Sappi Kirkniemi Mill in numbers. [3]

3 Theoretical background

This chapter gives general information on sludge drying, sludge incineration and alternative methods of sludge treatment in Finland as well as describes some important legislation and taxation issues related to incineration.

3.1 Sludge types

There are different types of sludge generated in different processes; they are subject to different standards and legislation and are also treated differently. This thesis only deals with sludge generated in paper industry and communal waste water treatment. Sludge types can be defined as follows:

Primary sludge: Or fibrous sludge is consisted of settleable solids which are removed from raw wastewater by using a physical process of primary settling. This sludge in normal circumstances consists mostly of fibres, fillers and pigments that have escaped the process at the paper machines. It settles on the primary clarifier and is collected. [4]

Biosludge: Also known as excess sludge, biological sludge, secondary sludge or activated sludge is produced aerobically in biological treatment. Biosludge mainly consists of micro-organisms and adsorbed suspended solids and colloids. The organic content of biological sludge varies between 60 and 80%, with a typical value of 75%.The biosludge from a paper mill can is comparable to communal biosludge although it has more wood based ingredients like lignin compounds and absorbed chlorine compounds. [4, 5]

Chemical sludge: Sludge that is collected from the flotation basin is called. Flotation polymer is added to the wastewater and it forms flocks with the solids in waste water. Is similar to biosludge in characteristics.

Municipal sewage sludge: Sludge that is generated in municipal waste water treatment plants is called municipal sewage sludge. As most of the large municipal waste water treatment plants also have primary clarifier as well as biological water treatment phase this sludge can technically be either primary or biological sludge but the important difference to the sludge, generated in paper mills and communities is that municipal sewage sludge contains human waste and is therefore treated differently. [4]

3.2 Sludge treatment and disposal

Sludge generated in treatment plants must be disposed. This can be done in several ways. The most commonly used methods are incineration, soil improvement, filling earth or, in some cases, landfilling. The disposal method is connected to characteristics of the sludge. Common problem to all sludge types is that they are mostly water. Before the sludge can be disposed in anyway, it has to be dewatered. Dewatering is done in stages; an example of the process is given in chapter 4. After the first stage of dewatering the dry content of the sludge is usually 15-25% (assuming using modern centrifuges). The following treatment methods are described using this as starting point. The pre-treated sludge is then treated usually by one of the following methods: composting, digesting, thermal drying, further mechanical drying or chemical treatment. One key component is also the transportation of the sludge. In many cases the generating site, treating site and disposal site are not in the same location. If the sites are not the same, the water content becomes important as transport fees are mainly weight based. There are three main overlapping goals for further sludge treatment: First to reduce the water content to avoid transporting water. Secondly to utilize the energy in the sludge by digestion and gas generation. Thirdly improve the dry content for incineration. Sludge incineration is dealt with more detail as it has more importance concerning this thesis project.

3.2.1 Sludge treatment and disposal methods

Composting is an aerobic treatment of the sludge. The treated sludge is mixed with support material such as peat and/or woodchips. The mixture is precomposted in a reactor and then composted in beet storage. After the composting process is finished, the product can be used for soil improvement or filling earth. Before the Sludge2Energy project in Kirkniemi this process was used. The reasons to move away from this process were economical. The transportation costs and fee for the treatment were high compared to thermal drying and incineration on site. [11]

Digesting: Is an anaerobic process where anaerobic bacteria is using the organic matter as food source and produce methane. The anaerobic digestion is a four stage process with following steps hydrolysis, acidogenesis, acetogenesis and methanogenesis.

The process can be illustrated with the heavily simplified chemical formula 1 below:

$$C_6H_{12}O_6 \rightarrow 3CO_2 + 3CH_4 \qquad (1)$$

The methane generated is either flared or combusted. After the digestion process is finished the product is usually further composted and then used as fill earth or for soil improvement.

Landfilling: According to the environmental policies in Finland an EU reducing land-filling and reuse of materials is encouraged by economic sanctions and is only done when limit values are exceeded in one or more substances in the sludge. In 2005 land-filling sludge was banned. Dewatered sludge can be used as filling earth after digestion or composting in a land fill if it does not meet the standards to other uses. [4, 11]

3.3 Sludge Incineration and sludge characteristics

When sludge is incinerated the characteristics of the sludge become important. Below on Table 1 are the characteristics of the biosludge generated at Kirkniemi mill's waste water treatment plant. There are four important figures in the table: dry content, ash content, sulphur content and the lower heat value.

Table 1: Sludge characteristics [6]

Dry content	87 %	Calorimetric Heat Value, dry	15,3MJ/kg
Dry content (analysis)	33 %	Lower Value, dry	14,24MJ/kg
Ash content 550°C, dry	32 %	Lower Value, as delivered	12,07MJ/kg
Carbon, C, dry	37 %	Delivered Energy, dry	3,96MWh/t
Hydrogen, H, dry	5 %	Delivered Energy, as delivered	3,35MWh/t
Nitrogen, N, dry	4 %		
Sulphur,S,dry	1 %		

Sulphur content largely determines if the flue gases need to be treated further than filtering the solid particles from the flue gas. The ash content both affects the heat value of the fuel and gives an estimate of the ash generation in the boiler. As the ashes need to be disposed in some method sludge incineration cannot be considered disposal method. In sludge incineration and in incineration of solid fuels generally, two types of ash is generated. Bottom ash of the boiler contains larger ash particles and sand if the incineration is done in sand bed boiler and any unburnt material. Fly ash consists of fine particles collected from flue gas flow with electrostatic precipitators, bag houses etc. These are used for example as fill earth if the contents do not exceed any limit values for heavy metals etc. if this is the case they must be treated.

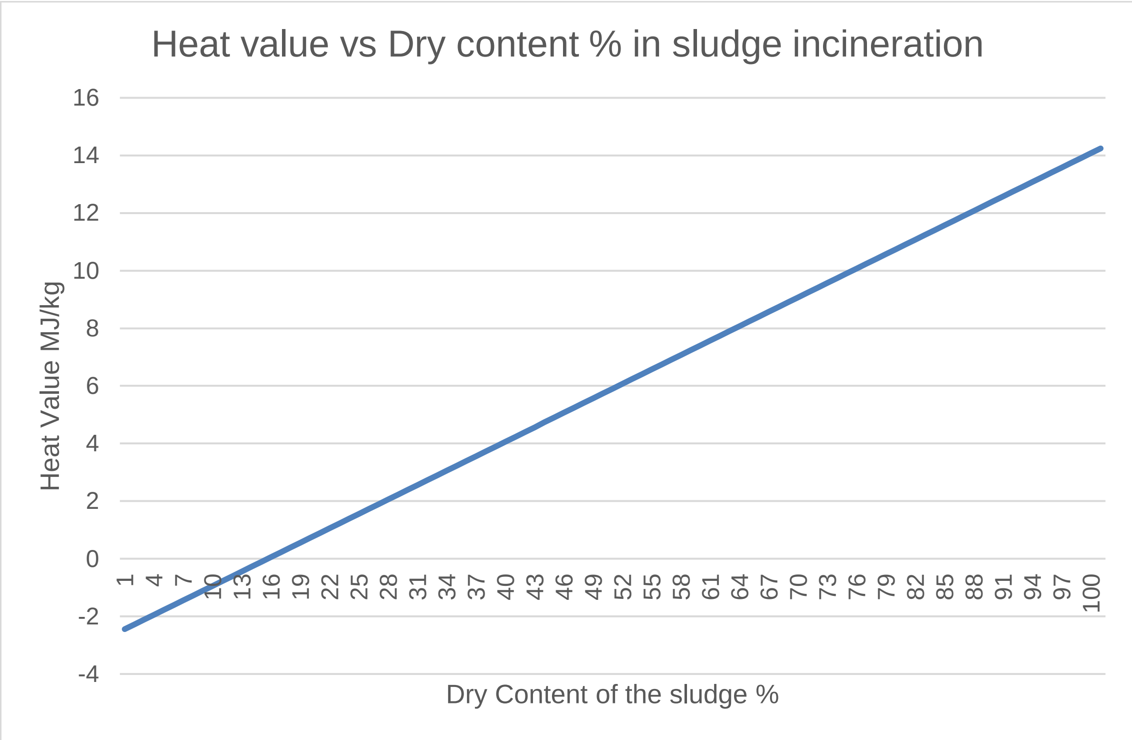

Figure 2: Heat value versus dry content at 14.2MJ/kg LHV

Figure 2 demonstrates the impact of the dry content to the heat value of the fuel. With the 14.2 MJ/kg lower heat value (LHV), the fuel starts to have a positive heat value near 15% dry content. If the heat value is negative it takes more energy to evaporate the water in fuel than is returned from the combustion.

3.4 Legislation and taxation

The definition of sludge in this thesis is a sludge generated at paper mill's wastewater treatment plant; communal wastewater is not treated in the same process. This is an important point because if communal wastewater is treated in the process the sludge is considered waste, and the incineration must be done according to waste incineration standards. However, sludge generated only from paper mill's process waters is considered a by-product of the process and is treated as a renewable fuel in terms of legislation and incineration standards. [11]

Renewable fuels are subject to feed tariffs in electricity generation until the end of 2015 and also benefit from heat premiums until the same date if the heat generated is utilized. [23]

Table 2: Feed tariffs [23]

Tariff period	Average market price (€/MWh)	Feed tariff(target price 83.50€/MWh)
2011 period 3	43,4	40,1
2011 period 4	37,39	46,11
2012 period 1	42,5	41
2012 period 2	32,41	51,09
2012 period 3	30,85	52,65
2012 period 4	40,83	42,67
2013 period 1	42,09	41,41
2013 period 2	39,93	43,57
2013 period 3	42,7	40,8
2013 period 4	39,92	43,58

The feed tariff is calculated for a three month period and electricity target price is set to be 83.50(€/MWh). This is illustrated on Table 2 above. The difference of the target price and the three month average of spotmarket price is compensated for the electricity producer as feed tariff. Also heat premium of 20(€/MWh) is paid if the generated is utilized. [23]

As biosludge generated in the paper mill's wastewater treatment plant is considered a wood based fuel and therefore a renewable energy source it is not subject to an excise tax. [24]

Table 3: Excise tax rates for commonly used fuels [25]

Excise duty rates on electricity and certain fuels as of 1 January 2014

TAX RATE TABLE 1

Product	Product category	Energy content tax	Carbon dioxide tax	Strategic stockpile fee	Total
Coal, coal brickets, solid fuels produced from coal (€/t)	1	47.10	84.43	1.18	132.71
Natural gas (€/MWh)					
1.1.2013–31.12.2014	2	4.45	6.93	0.084	11.464
Valid as of 1 January 2015	2	6.65	6.93	0.084	13.664

TAX RATE TABLE 2

Product	Product category	Excise duty on energy	Strategic stockpile fee	Total
Electricity (c/kWh)				
— tax class I	1	1.89	0.013	1.903
— tax class II	2	0.69	0.013	0.703
Tall oil (c/kg)	3	19.21	0	19.21
Fuel peat (€/MWh)				
1.1.2013–31.12.2014	4	4.90	0	4.90
Valid as of 1 January 2015	4	5.90	0	5.90

As can be seen from Table 3 fuels in Finland are heavily taxed and this makes it very attractive for power companies to use renewable fuels. This has led to a market price rise of wood based fuel in recent years. [25, 26]

4 Review of the Process

This chapter describes the waste water treatment process and sludge drying process in the Kirkniemi paper mill. The treatment process is divided into three phases: mechanical, biological and chemical. Sludge is collected from each phase of the process. The collected sludge is treated in two separate treatment lines both leading to incineration in the power plant Boiler 2. The process is visualized in Figure 3 on next page.

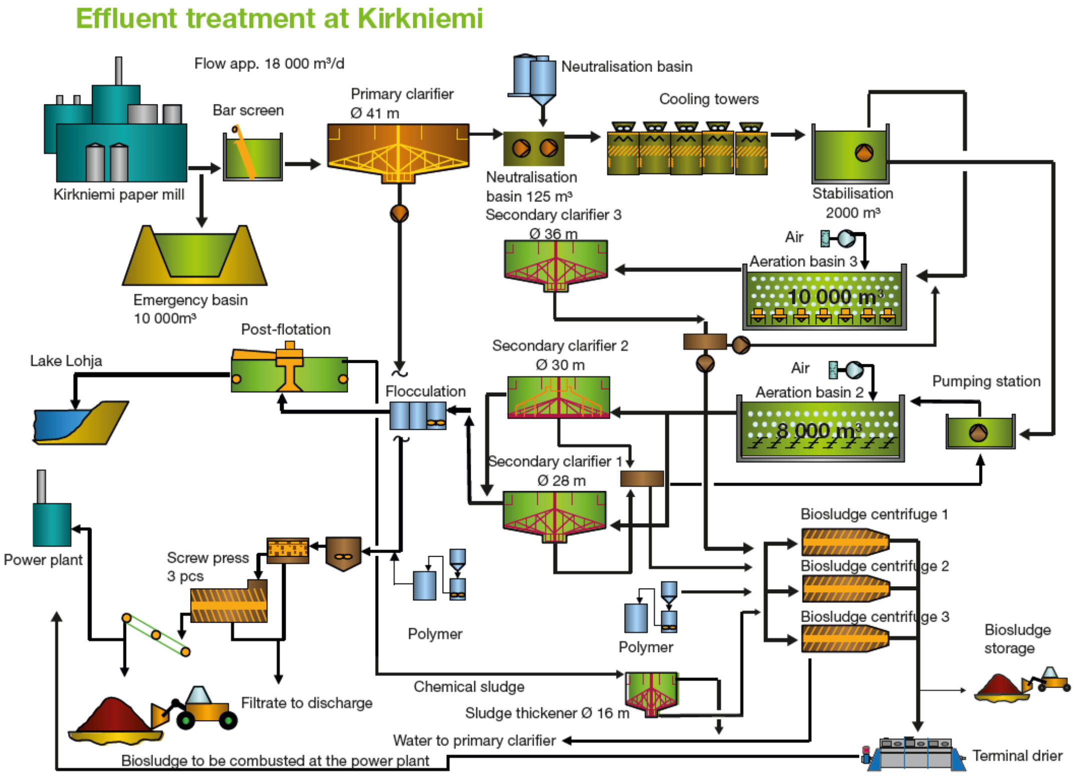

Figure 3: Effluent treatment at Kirkniemi [2]

4.1 Waste Water Treatment

The waste water treatment starts with the mechanical phase. The waste water enters the waste water treatment plant through a bar grid that removes larger solid objects from the waste water flow. Then the water flows to the primary clarifier. The primary clarifier is a 3.5-m-deep, 41-m-diameter round pool which has a turning bridge with submerged drag and a surface drag. The water enters in middle of the pool and is spread evenly. The water starts to flow towards the edges at approximately 3m/h. Primary clarifier works by gravity settling; the heavy particles in the waste water start to sink towards the bottom of the clarifier, and the surface water starts to clarify. The clarified surface water is collected from the edges of the pool and flows to neutralization pool and continues to equalization pool. Sludge is collected from both, surface and from the bottom of the pool. The surface sludge is pumped to thickening pool, and the sludge sinking to the bottom of the pool, called primary sludge, or often in paper industry fibrous sludge, is pumped to the power plant for further treatment.

The biological waste water treatment in Kirkniemi is an activated sludge process. The biological phase of the treatment process starts after the equalization pool. In the equalization pool the waste water is divided to separate biological treatment lines. The flows to each of the line are almost equal, treatment line 3 taking a slight majority of the flow. As can be seen in Figure 3 the flow is divided leading to Aeration pools 1 and 3 and from there further on to Secondary Clarifiers 1 and 2 from Aeration pool 1 and to Secondary clarifier 3 from Aeration Pool 3. The principle on both lines is the same and the principle is illustrated on figure 4.

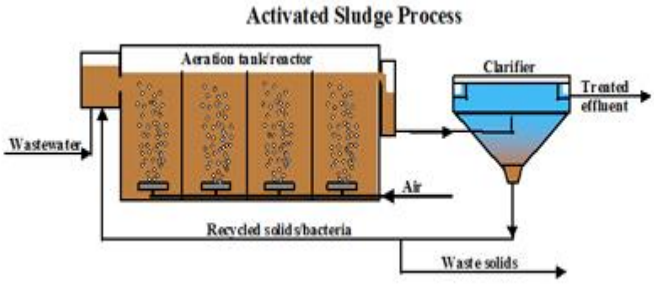

Figure 4: The principle of activated sludge process. [12]

In the activated sludge process, microbes are utilized to purify the water. The microbes in the aeration pool are using the organic compounds in the waste water as a food source. As the microbe colonies grow, they form flocks that can be removed from the waste water. In the aeration pool, the waste water is aerated from the bottom of the pool to give the microbes the necessary oxygen. Microbes grow and form flocks in the aeration pool and from the surface of the pool flow is led to a secondary clarifier. The secondary clarifier works similarly with the primary clarifier. The flocks formed by the microbes are settling towards the bottom of the pool. The sludge flow from the secondary clarifier is divided and the majority of sludge is circulated back to the aeration pool. Typically a 5% of the flow is divided and pumped for sludge treatment. This sludge is called biosludge or sometimes excess sludge. Surface sludge is also collected from secondary clarifiers and is pumped to a thickening pool. It is important for the process that the environment for microbial growth are kept stabile; temperature, pH, amount of nutrients and organic compounds are kept in balance. The balance of nutrients and organic compounds is the main difference between communal waste waters and waste water generated at the paper mill. The waste water generated the paper mill is poor in nutrients and those are actually added to the waste water. In Kirkniemi mill, ammonium water and phosphoric acid are added to the waste water at this stage to maintain the nutrient balance. [13]

Final phase in Kirkniemi Mill's waste water treatment is the chemical phase. Wastewater entering from the secondary clarifiers is mixed with flotation polymer. Then small air bubbles are pressed to the water; this is done by adding dispersion water to the flow. The polymer and particles are forming flocks in the waste water, and in the flotation basin the small air bubbles in the water are lifting the formed flocks to the surface of the basin where they are collected by a turning bridge with a drum shovel. The sludge collected is called chemical sludge, and is pumped to the thickening pool and then to the centrifuges

4.2 Sludge Treatment

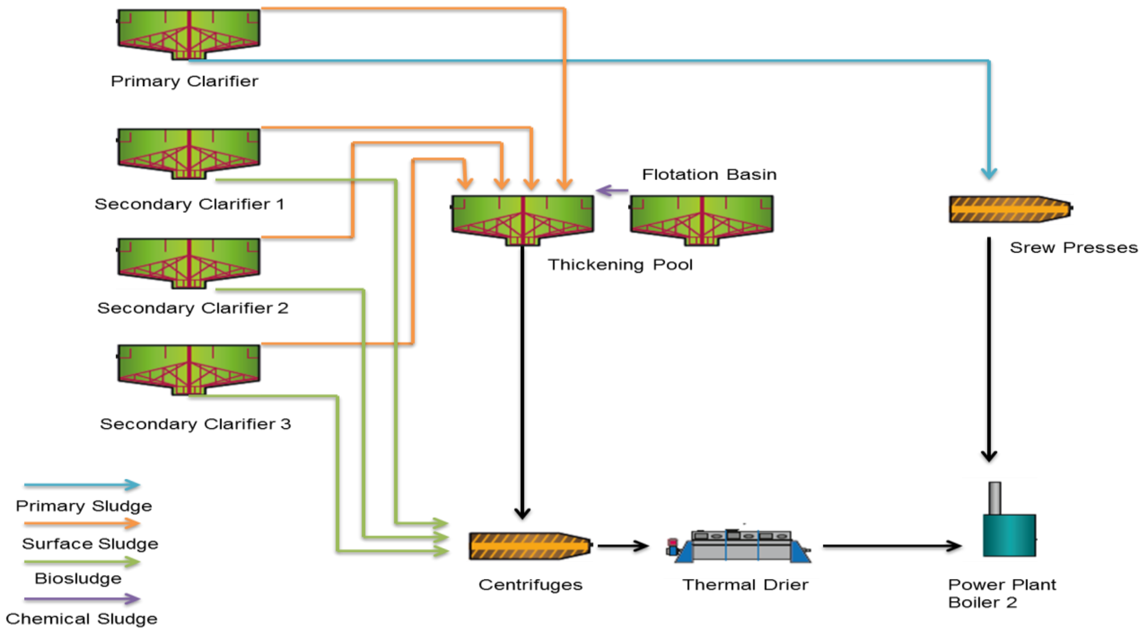

Figure 5: Sludge flows in Kirkniemi

Basically sludge in Kirkniemi mill is treated in two separate sludge treatment lines. The sludge flows are illustrated in Figure 5. Primary sludge collected from the primary clarifier is pumped directly to the power plant where it is mixed with polymer and then dried in screw presses. After this, it is conveyed to Boiler 2 and incinerated. Surface sludge from primary clarifier and all of the three secondary clarifiers are first pumped to thickening pool. Thickening pool is simply a tank with an entry pipe in the middle of the tank, overflow from the top of the tank with a pipeline back to the primary clarifier and there is an accept pipeline leading to centrifuges. It uses gravity settling to thicken the sludge. The excess biosludge collected from the three secondary clarifiers is pumped to centrifuges for drying.

4.2.1 Centrifugal Sludge Drying

The biosludge generated at the waste water treatment plant is mechanically dewatered with centrifuges. There are three centrifuges in the waste water treatment plant. Two are manufactured by AlfaLaval, types NX4500 and ALDEC G2-70 and one Noxon DC40. All of the centrifuges are decanter centrifuges. Before entering the centrifuges, the sludge is mixed with polymer that binds the solids together and improves the treatment otherwise the particles would be so small that they could escape with the reject waters.

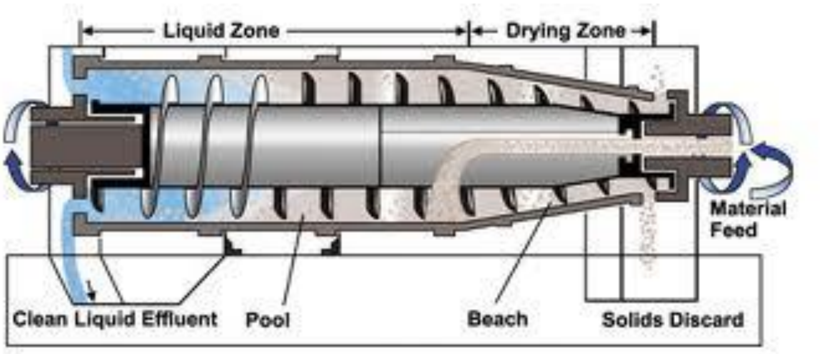

Figure 6: The working principle of decanter centrifuge [14]

The working principle of all three centrifuges is similar to that illustrated in Figure 6. The centrifuge has a cylindrical bowl and a screw conveyer. The sludge enters the centrifuge and is accelerated with an inlet rotor. This creates a centrifugal force that pushes solids to collect on the wall of the cylindrical bowl. The bowl and the screw conveyer are rotating to a same direction but with different speeds which moves the solids collected against the wall of the bowl to move towards the conical end of the bowl where the solids are discarded. The reject or clean effluent is flowing from the other end of the centrifuge and flows back to the primary clarifier. After centrifugal drying, the dry content of the sludge cake varies between 15-25% depending on the characteristics of the sludge. AlfaLaval states that the G2 model can reach a dry content as high as 30%. [15]

4.2.2 Thermal Sludge Drying

In thermal drying the mechanically dewatered sludge is further dried from an approximate dry content of 18% to a dry content of over 85%. The predried sludge from the centrifuges is conveyed to the thermal drier via screw conveyers. Figure 7 on next page illustrates this.

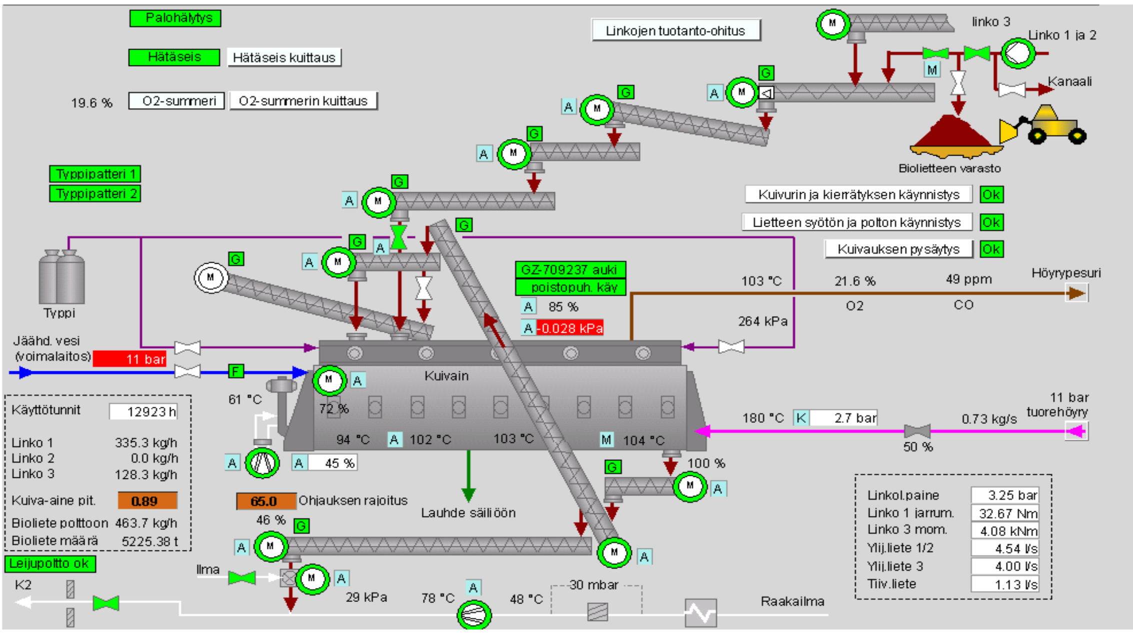

Figure 7: Haarslev Thermal drier process diagram from Alcont automation system.

The thermal drier used in Kirkniemi is a rotary disc drier manufactured by a Denmark-based company Haarslev Industries. The sludge enters the thermal drier from the left (red arrows). Inside the thermal drier is a steam-heated rotor with 50 discs equipped with paddles. The discs heat up the sludge, and the paddles move it towards the other end of the thermal drier. Dried sludge is collected from the other end, and part of it is recirculated back to feed and part is pneumatically conveyed to Boiler 2 for incineration. The thermal drier lies on two scales; weighting it constantly the automation system tries to keep the weight and therefore the amount of biosludge in the drier constant. The excess is conveyed for incineration. The thermal drier is heated with 11 bar live steam from the power plant. The condensate is returned back to the power plant. [16]

The exhaust mostly consisting of water vapour is led to a steam washer and vapour condenser by an exhaust suction pump. This keeps the dust and odour from spreading to the environment. After the vapour is washed from dust and solids in the steam washer, the water in the vapour is condensed in the vapour condenser, and the remaining gases are led to the intake of the pneumatic conveyer and blown to Boiler 2. The condensate is pumped back to the primary clarifier. [16]

4.3 Sludge Incineration

The dried sludge is incinerated at Kirkniemi Mill's power plant in Boiler 2. Boiler 2 is a fluidized sand bed boiler (FCB) built on 1978. It has a fuel power of 40MW and produces 15kg of 520C / 80bar steam. It uses primarily wood based fuels: wood waste from the mill's debarking plant and purchased biofuel. Also primary sludge and biosludge are combusted in this boiler. Fluidized bed boilers are well suited for combusting low grade solid fuels. The boiler is equipped with two electrostatic precipitators (ESP) removing particles from the flue gas. [17]

The aim of this thesis was to create a method to acquire knowledge of how much biosludge is incinerated in the power plant's Boiler 2.

5 Problem Definition and Research Methodology

This chapter first defines the goals of this thesis project, and then describes the steps taken to achieve them.

5.1 Problem Definition

Kirkniemi Mill had invested in to a thermal biosludge drier that dries sludge from the waste water treatment plant and conveys it for combustion in Boiler 2 but at the starting point of this thesis the mass flow of the sludge was unknown and the energy in the fuel could not be calculated.

The thesis work had two main goals:

- First, the aim was to create a calculation system for the mass flow of biosludge in to the boiler and derive the energy input from that.
- Secondly, the Energy and water department wanted to know how much biosludge had already been incinerated before a method to calculate this was implemented.

As all the machinery were installed already at the starting point of the thesis and the department wanted to keep the expenses at minimum information sources already available had to be used. The biosludge incineration on Boiler 2 started on February 2012; when this thesis project begun on June 2012, sludge had been incinerated already for 5 months.

5.2 Estimating the Sludge Incinerated Prior to the Calculation System

The first step in this thesis project was to estimate the amount of sludge incinerated before an implemented calculation system and to create the calculation system itself. Before the incineration started, the sludge was transported off site for composting, and the department had load reports. Also the amount of sludge created has to have a connection to the amount of paper produced. Even they are probably not directly proportional to each other this information was to be used. A one-year time span was used to reduce effects of malfunctions or other disturbances in the factory or in the waste water treatment plant that could increase the amount of sludge created or reduce the effectiveness of the biological phase of the waste water treatment.

Table 4 was generated by comparing the weighting documents of the sludge loads transported of site and paper production data. Average of one year was calculated and a figure of 25,9kg of biosludge per ton of paper was acquired. This figure was used to estimate the amount of biosludge combusted and later to compare with the results of the calculation systems. It is important to note that the sludge amounts are in assumed dry content of 18%. The standard deviation of sludge generated is high and the likely explanation for this is that the sludge was not transported off site daily but the sludge loads could have been stacked to certain months.

Table 4: Biosludge generation compared to paper production [7, 8, and 9]

	biosludge (t) dry content 18 %	Production (t)	kg of sludge per paper ton
February 2011	1280,68	51100,8	25,06
March 2011	2271,31	64106,7	35,43
April 2011	1889,2	54159,7	34,88
May 2011	1113,2	56106,8	19,84
June 2011	1315,94	57196,2	23,01
July 2011	1551,05	56223,8	27,59
August 2011	1533,65	54186,5	28,30
September 2011	1366,2	69129,6	19,76
October 2011	1511,42	53055,5	28,49
November 2011	830,82	55337,1	15,01
December 2011	1186,14	53519,5	22,16
January 2012	1779,02	55908,1	31,82
TOTAL	17628,63	680030,30	Average: 25,9
STD	366,6	4831,9	6,0

When the data is plotted as a graph (Figure 8), it is clear that the sludge generation is not directly tied to the production.

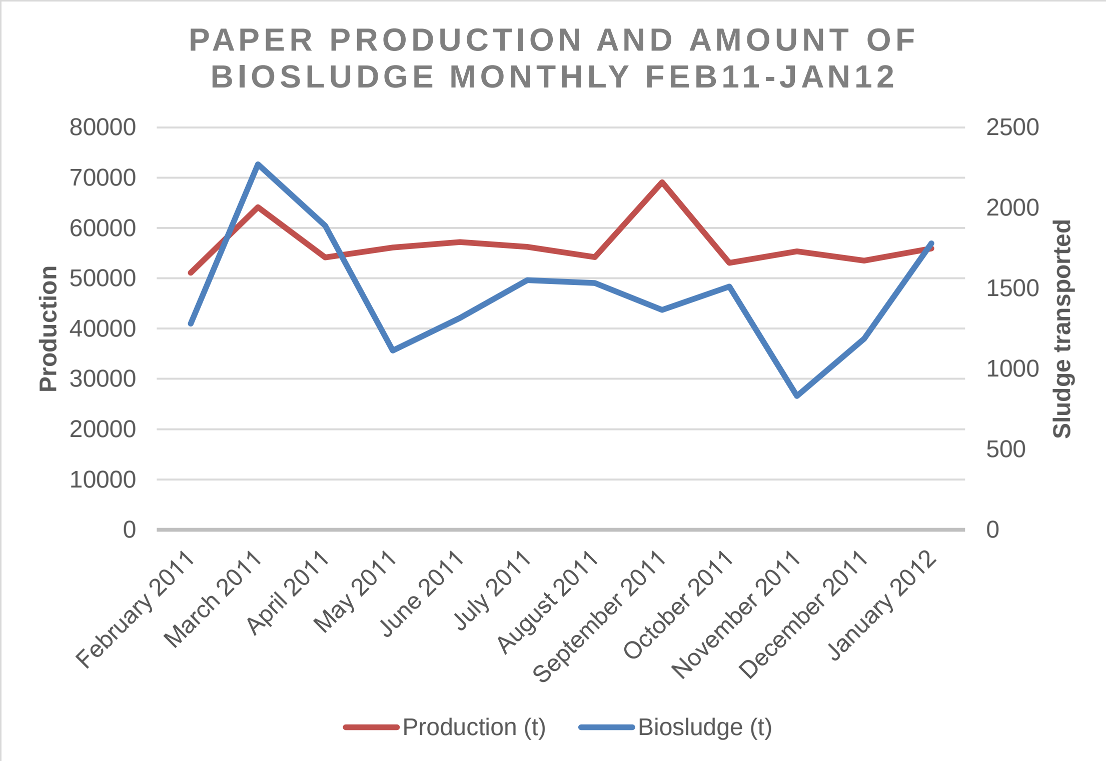

Figure 8: Paper production and biosludge generation February 2011 - January 2012[7, 8, and 9]

There was a process change in the ground wood mill on December 2011. The mechanical pulp has since been washed in wire presses. This could have significantly increased the amount of solids entering the waste water plant. It is also important to note that no dry content measurements were done for the sludge transported off site. This apparently did not seem to be important as the payment for the treatment was paid per ton of sludge regardless of the dry content. After consulting the staff at the Energy and Water Department, dry content of 18% was decided to be used in the calculations. The real average dry content could be considerably higher.

The estimation of biosludge incineration during the time the incineration started and a calculation system implemented was derived from the 25.9kg of biosludge per paper ton produced and from the dry content measurement carried out on the thermal drier.

5.3 Parameters needed for a Calculation System

To create a mass flow calculation system information of consistencies and volume flows were needed. In the mechanical dewatering process, all necessary flow and consistency meters were available to collect online data. Laboratory testing was done biweekly on return sludge from Secondary Clarifier 3 and Secondary Clarifiers 1 and 2. The values from return sludge can be used for biosludge or, in this case, excess sludge as it is a cut from the main flow. The flow in a pipeline from thickening pool to the centrifuges was not laboratory tested at this point. A sampling place for this pipeline was constructed after the failure of the automated calculation system. All flows and consistencies were known on the implementation of the calculation system. There are returning flows from the centrifuges and from the thermal drier’s steam washer, and these flows had to be estimated and counted.

5.3.1 Estimating Reject Waters

Reject waters are returning flows from the centrifuges and biosludge drier that are returning to primary clarifier. In centrifuges, the incoming sludge is thickened by centrifugal force and the filtrate that mostly consists of water is called reject water. In the biosludge drier, the sludge is thickened by heat and the evaporated steam is sucked with vacuum to steam washer and this vacuum sucks in some of the dried sludge as well. The flow from steam washer is considered reject water.

The reject waters of the centrifuges are returned to primary clarifier. As the reject waters do not flow in a full pipe and there is no sampling possibility for the reject waters, the only alternative to estimate the amount of solids returning to the primary clarifier was to trust the manufacturers. According to the manufacturers all of the three centrifuges are capturing at least 95% of the solids. A correction multiplier 0.95 used in the calculations derives from here. [18, 19, 20]

The reject water returning to the primary clarifier from the steam washer of the thermal drier was estimated empirically. Following sampling plan was made: The volume flow was to be measured with a portable flow meter, and consistency samples would be taken four times 1 litre over 8 hour shift with approximately two hours between the samples. The consistency samples were then to be analysed in the mill’s laboratory. The experiment was carried out three times on July 23th, 26th and 27th of 2012.

Fluxus ADM6725 portable flow meter was assembled to the pipeline with following setup:

Pipe :
Outer Diameter : 33,8 mm
Wall Thickness : 1,6 mm
Roughness : 0,3 mm
Pipe Material : Stainless Steel
Lining : WITHOUT LINING
Medium : Water
Medium Temperature.: 85 C
Transducer Type : Q3N74019
Sound Path : 2 NUM

The data collected can be seen on Table 5 below.

Table 5: The mass flow of solids returning to primary clarifier from the steam washer.

	Avg.Flow m3/h	Consistency g/l	Mass Flow kg/h	Mass Flow kg/d	Mass Flow ton/month
23rd June	1,73	14,83	25,66	615,78	18,47
26th June	1,71	14,40	24,62	590,93	17,73
27th June	1,79	14,88	26,63	639,20	19,18
Average	1,74	14,70	25,63	615,17	18,46

When comparing the results with the comparison value acquired earlier, this was first suggesting a solid loss to the primary clarifier to be as high as 7%. Checking the known flows and consistencies from TIPS on 23rd to 27th of July, this was considered too high, and 5% was used instead. The correction factor of 0.95 for the reject water from the thermal drier's steam washer is derived from here.[21]

5.3.2 Measurement Equipment for Online Calculation System

There are eight relevant measurement devices in the waste water treatment plant. Four electromagnetic flow meters, three ultrasound consistency meters and one optical consistency meter. The needed devices and laboratory tests are listed below. They are coded as follows: Identify code for EA, Identify code used in the mill, description of device or test.

- VM1, FC-709073, Krohne IFS 4000/6 electromagnetic flow meter located in downstairs of the centrifuge room.
- VM2, FC-709071, Krohne IFS 4000/6 electromagnetic flow meter located in downstairs of the centrifuge room.
- VM3, FC-709354, Krohne IFS 4000/6 electromagnetic flow meter located in the polymer room.
- VM4, FC-709205, Krohne Optiflux electromagnetic flow meter located next to the Centrifuge 3.
- SM1 QI-709074, KDG Mobrey MSM40 ultrasound consistency meter located in the downstairs of the centrifuge room.
- SM2 QI-709072, KDG Mobrey MSM40 ultrasound consistency meter located in the downstairs of the centrifuge room.
- SM3 QI-709442, KDG Mobrey MSM40 ultrasound consistency meter located in the downstairs of the centrifuge room.
- SM4 QI-709206, Lange (specific type unknown) laser optical consistency meter located next to the Centrifuge 3.

5.4 Online Calculation system

The First attempt was to create a fully automated mass flow calculation system. After a study of the Alcont automation system and the actual piping at the wastewater treatment plant, a calculation system was designed and then programmed to the automation system. The automated calculation system is illustrated in Figure 9. on the next page

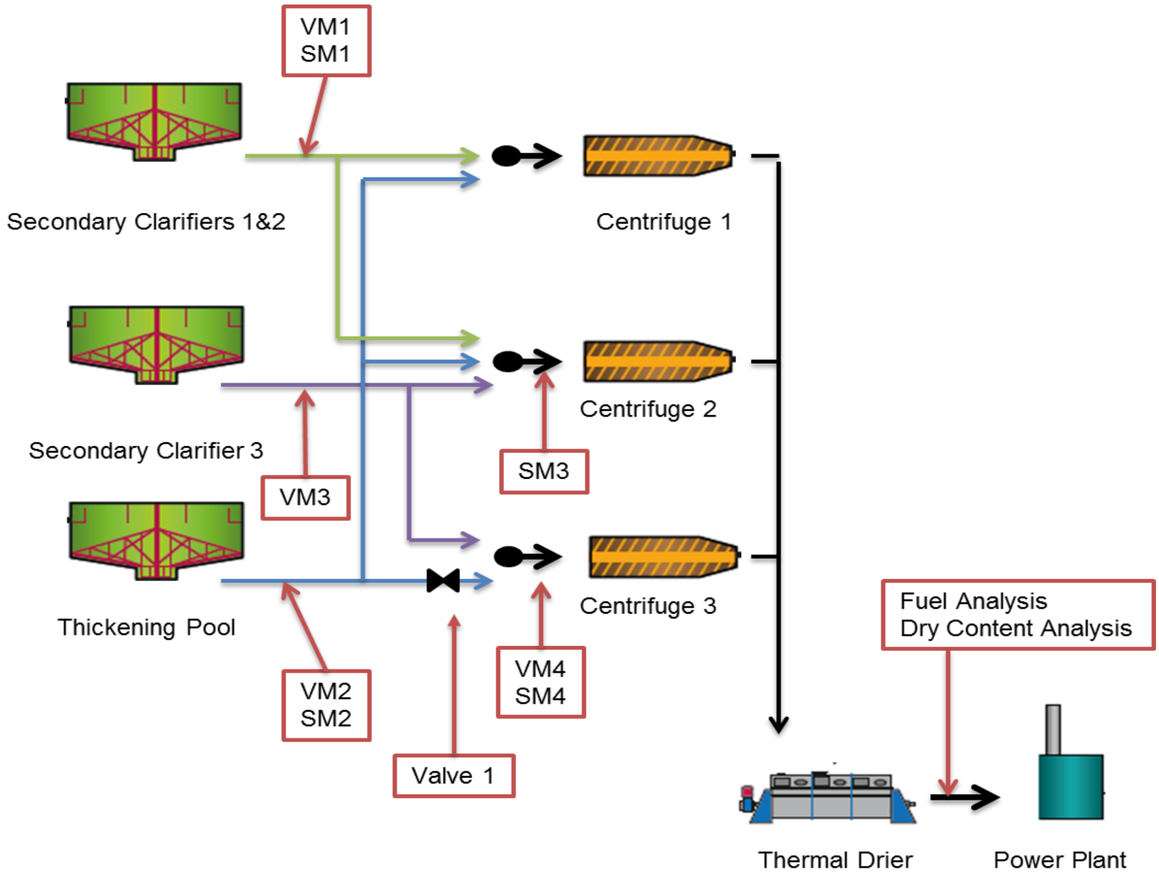

Figure 9: Automated Calculation System

The key devices and measurement points used in the automated calculation system can be seen in Figure 9. This system expects that the excess sludge from Secondary Clarifiers 1 and 2 is dewatered in Centrifuge 1 and the excess sludge from Secondary Clarifier 3 is dewatered in Centrifuge 3. Centrifuge 2 is normally in reserve and if either of centrifuges 1 or 3 is offline it is taken to use as replacement.

List of variables and conditions used in the program and the used calculation formula are presented below:

Centrifuge 1: $\big((VM1 * SM1) + (VM2 * SM2)\big) * 0.95 * C1On$

VM1 = (FC-709073) Secondary Clarifier 1/2 excess sludge flow

SM1 = (QI-709074) Secondary Clarifier 1/2 excess sludge consistency

VM2 = (FC-709071) Thickening basin flow

SM2 = (QI-709072) Thickening basin consistency

0,95 =correction multiplier (reject waters from centrifuge 1)

C1On =Centrifuge 1: Online/Offline, if online=1 if offline=0

Centrifuge 2: $\Big(\big((VM1 + VM2 + VM3) * SM3 * 0.95\big) - \Big(\big((VM1 * SM1) + (VM2 * SM2)\big) * 0.95 * C1On\Big)\Big) * C2On * V1$

VM1 =(FC-709073) Secondary Clarifier 1/2 excess sludge flow

VM2 =(FC-709071) Thickening basin flow

VM3 =(FC-709354) Secondary Clarifier 3 excess sludge flow

SM3 =(QI-709442) Centrifuge 2 incoming consistency

0,95 correction multiplier (reject waters from centrifuge 2)

C2On = Centrifuge 2: Online/Offline, if online=1 if offline=0

V1= If Valve 1 (HS-709201) is OPEN → VM2 (FC-709071) = 0 (to avoid duplicate calculation of flow VM2)

Centrifuge 1 flow is deducted to avoid duplicate summing.

Centrifuge 3: $\big((VM4 * SM4) * 0.95\big) * C3On$

VM4 (FI-709205) Centrifuge 3 incoming flow

SM4 (QI-709206) Centrifuge 3 incoming consistency

0,95 correction multiplier (reject waters from centrifuge 3)

C3On = Centrifuge 3: Online/Offline, if online=1 if offline=0

Other multipliers: $\times\, 0{,}95 \times 86{,}4$

0,95 biosludge drier correction multiplier (steam washer reject waters)

86,4 unit change g/s → kg/d

The mass flow from the biosludge drier to the Boiler 2 can therefore be calculated with the following formula:

$$(\Big(\big((VM1 * SM1) + (VM2 * SM2)\big) * 0.95 * C1On\Big) + \Big(\Big(\big((VM1 + VM2 + VM3) * SM3 * 0.95\big) - \Big(\big((VM1 * SM1) + (VM2 * SM2)\big) * 0.95 * C1On\Big)\Big) * C2On * V1\Big) + \Big(\big((VM4 * SM4) * 0.95\big) * C3On\Big)) * 0.95 * 86.4 = [\frac{kg}{d}]$$

Figure 10 is a screenshot taken from the Alcont automation system after the online mass flow calculation system was completed and programmed. English translations for the terms from top to bottom in the red outlined box are running hours, Centrifuge 1 output (100% dry content), Centrifuge 2 output (100% dry content), Centrifuge 3 output (100% dry content), dry content after thermal drier, biosludge incinerated in Boiler 2 and total incinerated biosludge. This was the first attempt to create a calculation system for the mass flow of thermally dried sludge to Boiler 2.

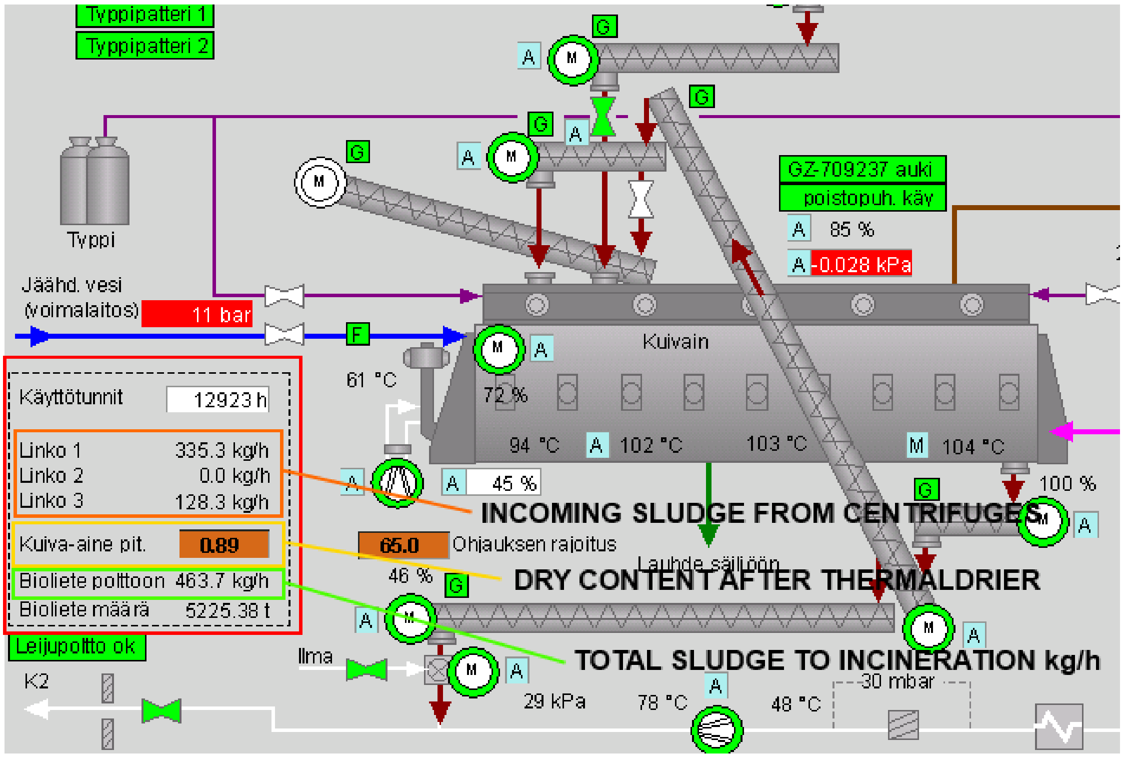

Figure 10: The calculation system on the Alcont automation system.

5.4.1 Reliability problems

Upon implementation, the system seemed to give reliable numbers at first, but the difference between the laboratory results and online consistency meters became clear. The scale of the error was too large to be ignored, and the online calculation system was abandoned.

5.5 The Implemented Calculation System

After the failure of the fully automated system a backup plan was taken to use. It was agreed that the online flow meters were accurate enough and the problem lied in the consistency meters. According to the electricians on the Water and Energy Department, calibration of the online consistency meters had been tried before and had proved useless.

After going through the lab testing list, it was noticed that the excess sludge from the secondary clarifiers was studied already twice per week. The only missing element was the thickened sludge. New sampling site for thickened sludge was constructed, and the testing of the sludge was added to the sampling schedule.

The resulting calculation system is very simple. The automation system collects data from the sludge flows, and the consistency of excess sludge from Secondary Clarifiers 1 and 2, Secondary Clarifier 3 and from the thickening pool is tested twice per week by the factory laboratory. The needed devices and laboratory tests are listed below. They are coded as follows: Identify code for EA, Identify code used in the mill, description of device or test.

- VM1, FC-709073, Krohne IFS 4000/6 electromagnetic flow meter located in the downstairs of the centrifuge room.
- VM2, FC-709071, Krohne IFS 4000/6 electromagnetic flow meter located in the downstairs of the centrifuge room.
- VM3, FC-709354, Krohne IFS 4000/6 electromagnetic flow meter located in the polymer room.
- SM1, Consistency Analysis of excess sludge from Secondary Clarifiers 1 and 2, Kirkniemi Mill Laboratory: a 5 litre sample is analysed according to the SFS 3037 standard except that MN 651 paper filters by Macherey-Nagel are used instead of glass fibre filters.
- SM2, Consistency Analysis of excess sludge from Secondary Clarifier 3, Kirkniemi Mill Laboratory: a 5 litre sample is analysed according to the SFS 3037 standard except that MN 651 paper filters by Macherey-Nagel are used instead of glass fibre filters.
- SM3, Consistency Analysis of excess sludge from thickening pool, Kirkniemi Mill Laboratory: a 5 litre sample is analysed according to the SFS 3037 standard except that MN 651 paper filters by Macherey-Nagel are used instead of glass fibre filters.

As flows and consistencies from each sludge sources were known, the information of flows and consistencies to a single centrifuge was no more relevant. The mass flow could be simply calculated by multiplying the flows and consistencies for each source of sludge. The implemented calculation system is illustrated below in Figure 11.

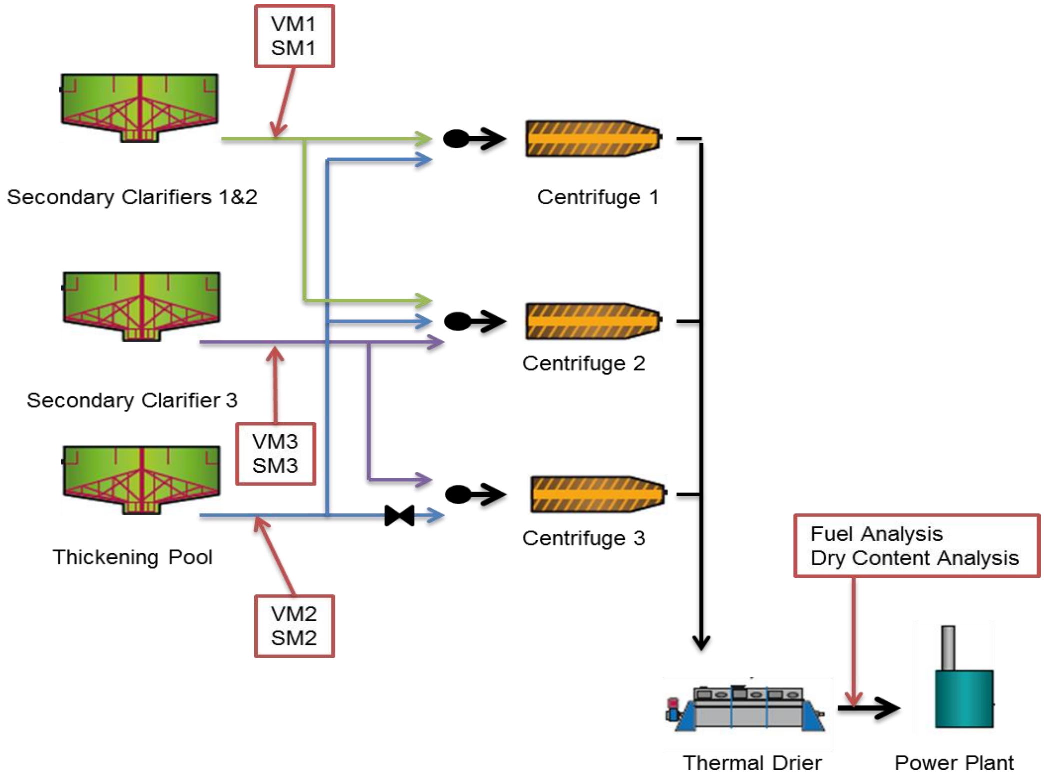

Figure 11: The Implemented Calculation system

Variables used in the calculation are listed below:

VM1 = (FC-709073) excess sludge secondary clarifier 1/2 flow (online meter)

VM2 = (FC-709071) thickened sludge flow (online meter)

VM3 = (FC-709354) excess sludge secondary clarifier 3 flow (online meter)

SM1 = excess sludge secondary clarifier JS1/2 consistency (laboratory test)

SM2 = thickened sludge consistency (laboratory test)

SM3 = excess sludge secondary clarifier JS3 consistency (laboratory test)

0,9025 = correction multiplier for centrifuges and biosludge drier's reject waters

86,4 = g/s -> kg/d unit change

The mass flow can therefore be calculated with the following formula:

$$(((\mathrm{VM1} * \mathrm{SM1}) + (\mathrm{VM2} * \mathrm{SM2}) + (\mathrm{VM3} * \mathrm{SM3})) * 0{,}9025) * 86{,}4 = [\frac{\mathrm{kg}}{\mathrm{d}}]$$

6 Results

6.1 Information Required by the Energy Authority

The goal of the thesis work was to create a mass flow calculation system for incinerated biosludge. The following information regarding biosludge incineration was sent to EMA. The mass flow is calculated according to the implemented calculation system with the following formula:

$$(((\mathrm{VM1} * \mathrm{SM1}) + (\mathrm{VM2} * \mathrm{SM2}) + (\mathrm{VM3} * \mathrm{SM3})) * 0{,}9025) * 86{,}4 = [\frac{\mathrm{kg}}{\mathrm{d}}]$$

The consistencies SM1, SM2 and SM3 are tested three times per week by Kirkniemi Mill Laboratory. A 5 litre sample is analysed accordingly to SFS 3037 standard except that MN 651 paper filters by Macherey-Nagel are used instead of glass fibre filters.

The goal of the project was to create a system that provides information of how much biosludge was incinerated and how much of energy it contains. For this, the mass flow to the Boiler 2 is needed and the lower heat value of the biosludge. Thus two formulas are needed.

The energy the fuel contains is calculated with the following formula:

$$\frac{\left(LVH * \frac{100-\theta}{100}\right) - (0{,}02441 * \theta)}{3600} * kg(sludge) = [MWh]$$

Where LVH= Lower heat value, θ= water content, 0,02441 evaporation constant at NTP

Water content of the sludge is determined by dry content analysis of thermally dried sludge by the Kirkniemi Mill Laboratory: The sample (approximately 100g) is taken from a sampling fitting above the thermal drier’s block feeder once per week. The sample is sealed in a plastic bag and delivered to the laboratory. Then 50g of the sample is taken for an analysis in the laboratory and dried for 2 hours at 105 degrees Celsius in a convection oven. The weight difference is measured. This is a CEN/TS 14774-3 Finas accredited method.

The lower heat value is obtained with a heat value analysis of thermally dried sludge. This is done in an external laboratory: The sample (approximately 2 litres) is taken from a sampling fitting above the thermal drier’s block feeder once per week. The sample is sealed in a plastic bag and delivered to the laboratory. The sample is combusted in bomb calorimeter with pure oxygen and the heating impact on surroundings is measured. This is a CEN/TS 14918 Finas accredited method.

6.2 Example Calculation Sheet

The full calculation sheet for May 2013 can be found in Appendix 1. Important parts of it are illustrated in Table 6 below.

Table 6: Example Calculation Sheet

	Mass Flow	Dry Content	MWh
	kg/d	%	
1.5.2013	12080	88,8	41,5
2.5.2013	12052	88,8	41,4
3.5.2013	11796	88,8	40,5
4.5.2013	12376	88,8	42,5
5.5.2013	12890	88,8	44,3
6.5.2013	12865	88,8	44,2
7.5.2013	12539	86,5	41,8
8.5.2013	12807	86,5	42,6
9.5.2013	12279	86,5	40,9
10.5.2013	11643	86,5	38,8
11.5.2013	11536	86,5	38,4
12.5.2013	11746	86,5	39,1
13.5.2013	11853	86,5	39,5
14.5.2013	13457	86,5	44,8
15.5.2013	14616	86,5	48,7
16.5.2013	14687	86,5	48,9
17.5.2013	11986	86,5	39,9
18.5.2013	11961	86,5	39,8
19.5.2013	11539	86,5	38,4
20.5.2013	12055	86,5	40,1
21.5.2013	13476	88,6	46,2
22.5.2013	11525	88,6	39,5
23.5.2013	12201	88,6	41,8
24.5.2013	12999	88,6	44,6
25.5.2013	13217	88,6	45,3
26.5.2013	13085	88,6	44,8
27.5.2013	12814	88,6	43,9
28.5.2013	13262	88,2	45,2
29.5.2013	13557	88,2	46,2
30.5.2013	14345	88,2	48,9
31.5.2013	14116	88,2	48,1

Calorimetric Heat Value (dry)	15,3	MJ/kg
Lower Heat Value	14,24	MJ/kg

$$\frac{\left(LVH * \frac{100-\theta}{100}\right) - (0{,}02441 * \theta)}{3600} * kg(sludge) = MWh$$

Total Mass Flow	393360	kg
Total Energy	1330,84	Mwh

The calculation sheet above is missing some steps that can be seen in Appendix 1. In the above table, the mass flows from secondary clarifiers and from the thickening pool are summed together already. The bottom right corner presents the total amount of sludge incinerated and the amount of energy in the fuel. A new calculation sheet is created for every month.

6.3 Comparison of Results

Table 7 compares sludge generation between 2011 and 2013.

Table 7: Comparison of sludge generation between February 2011-January 2012 and 2013 [7, 8, 9, 22]

	2011	2013
January		305
February	231	395
March	409	352
April	340	342
May	200	340
June	237	214
July	279	330
August	276	359
September	246	314
October	272	366
November	150	265
December	214	333
January	320	
Average	264	326
Total	3173	3916

Production	680030	647727
Sludge kg/Paper ton	4,67	6,05
STD of sludge produced monthly	65,9	46,1

In Table 4, the generated sludge is converted to 100% dry content. It can be seen from the table that sludge generation assuming both set of values are correct is roughly 30% higher on 2013. The standard deviation is considerably smaller on 2013 than on 2011 which was expected to the transportation timing. This is a high change in the three-year period of observation. There are five possible explanations for this:

1. There is no correlation between sludge generation and paper production.
2. The dry content estimation of 18% is too low.

3. There are major changes in processes that are leading to increased load on waste water treatment plant.
4. The effectiveness of biological phase in the process has improved significantly.
5. The increase has been caused by a combination of two or more of the above explanations.

6.3.1 Possible explanations

The most likely explanation of the 30% difference in sludge generation is that the estimation of 18% of dry content for the sludge transported of site was too low but there may be other factors as well.

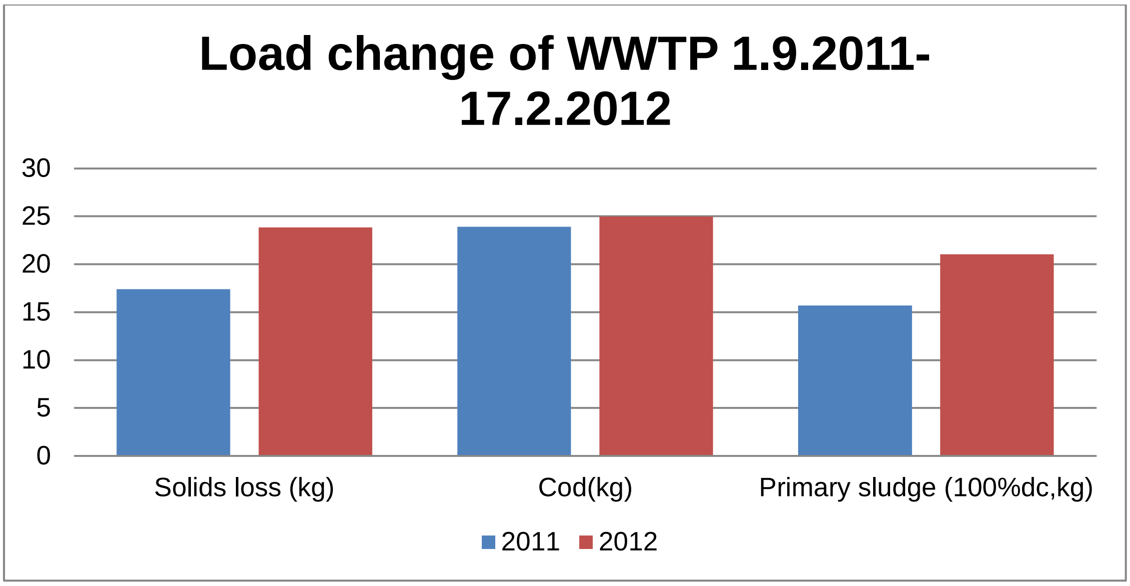

Figure 12: Load change of wastewater treatment plant per paper ton

On Figure 12 the solids loss, chemical oxygen demand (COD) and the primary sludge generated on the primary clarifier was studied between 1.9.2011 - 17.2.2012. There is a clear increase in solids loss and primary sludge generated. This can be partly explained by the installation of wire presses for pulp washing in GW-plant. The observation period is however too short to make any conclusions

7 Conclusions

The problem in comparing the data generated with the calculation system and the data gained from the sludge transport documents, is that there were no dry content measurements done. The dry content of 18% was an educated guess made by the power plant staff. If the dry content would have been assumed higher the comparison value would have been closer to the measured values from 2013.

The comparison value of 25.9kg of biosludge per paper ton was generated from the production data and transportation documents from February 2011 until January 2012 which was the last full month when biosludge was transported of site for composting. The data collected from the calculation system spans the year 2013. These years were quite different in terms of production. During the time comparison value was acquired the total production was 680 030 tons of paper. On 2013 the production was 647 727 tons of paper, and the paper mill suffered several commercial shutdowns. It was assumed that the sludge production correlates with the paper production but during shutdowns unused pulp and other raw materials are dumbed to the wastewater treatment plant which could reverse this assumption. Better method could have been correlating the sludge generation to the incoming waste water statistics instead of paper production,

The pulp washing in wire press at GW-mill started on December 2011. This, and other process changes might have an impact to the solids flow to the wastewater treatment plant. If the impacts of these would be an interest of study in the future the incoming waste water data in TIPS could give a more accurate answer to the changes in sludge generation. These problems are however, related to comparison of the results to past, not to the implemented calculation method itself.

By conclusion, the thesis project was a success. A simple and reliable calculation method was created without a need for investment or downtime in the process. The measurement method was accepted by the Finnish Energy Authority on 2013 and is in use.

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Appendix 1: Calculation Example

	Thickening Pool			Secondary Clarifier 1&2			Secondary Clarifier 3			Mass Flow	Dry Content	MWh
	Flow l/s	Consistency g/l	Mass Flow g/s	Flow l/s	Consistency g/l	Mass Flow g/s	Flow l/s	Consistency g/l	Mass Flow g/s	kg/d	%	
1.5.2013	1,3	6,04	7,7	5,8	16,2	94,0	3,4	10,6	35,9	12080	88,8	41,5
2.5.2013	1,4	6,04	8,5	5,8	16,0	92,9	3,4	10,6	35,9	12052	88,8	41,4
3.5.2013	1,4	6,04	8,5	5,7	15,3	87,0	3,4	11,4	38,9	11796	88,8	40,5
4.5.2013	1,4	6,04	8,5	6,2	15,3	94,7	3,3	11,4	37,8	12376	88,8	42,5
5.5.2013	1,4	6,04	8,5	6,6	15,2	100,6	3,3	11,4	37,8	12890	88,8	44,3
6.5.2013	1,4	6,04	8,5	6,6	15,4	101,4	3,2	11,4	36,6	12865	88,8	44,2
7.5.2013	1,4	1,84	2,6	6,6	15,3	101,2	3,1	11,4	35,3	12539	86,5	41,8
8.5.2013	0,9	1,84	1,7	6,6	15,1	99,3	3,6	11,4	41,0	12807	86,5	42,6
9.5.2013	0,9	1,84	1,7	6,6	14,3	94,6	3,5	11,4	39,9	12279	86,5	40,9
10.5.2013	1,0	1,84	1,9	6,6	14,0	92,5	3,6	9,7	34,8	11643	86,5	38,8
11.5.2013	1,0	1,84	1,9	6,6	13,8	91,3	3,6	9,7	34,8	11536	86,5	38,4
12.5.2013	1,0	1,84	1,9	6,7	14,0	93,7	3,6	9,7	34,8	11746	86,5	39,1
13.5.2013	1,0	1,84	1,9	6,8	14,0	94,9	3,6	9,7	34,8	11853	86,5	39,5
14.5.2013	1,0	1,69	1,8	6,6	18,0	119,1	3,6	7,9	28,4	13457	86,5	44,8
15.5.2013	1,2	1,69	2,0	6,6	20,0	131,7	3,6	7,9	28,4	14616	86,5	48,7
16.5.2013	1,2	1,69	2,0	6,6	20,1	132,5	3,6	7,9	28,4	14687	86,5	48,9
17.5.2013	1,2	1,69	2,0	5,5	16,5	91,0	3,6	11,1	40,0	11986	86,5	39,9
18.5.2013	1,2	1,69	2,0	5,5	16,5	90,7	3,6	11,1	40,0	11961	86,5	39,8
19.5.2013	1,2	1,69	2,0	5,5	15,6	86,0	3,6	11,1	40,0	11539	86,5	38,4
20.5.2013	1,2	1,69	2,0	5,9	15,6	91,7	3,6	11,1	40,0	12055	86,5	40,1
21.5.2013	1,2	2,01	2,4	6,1	18,2	111,1	3,6	11,0	39,6	13476	88,6	46,2
22.5.2013	1,2	2,01	2,4	6	14,8	89,0	3,6	11,0	39,6	11525	88,6	39,5
23.5.2013	1,2	2,01	2,4	6,2	15,6	96,7	3,6	11,0	39,6	12201	88,6	41,8
24.5.2013	1,2	2,01	2,4	6,2	15,1	93,8	3,6	14,3	51,5	12999	88,6	44,6
25.5.2013	1,2	2,01	2,4	6,2	15,5	96,3	3,6	14,3	51,5	13217	88,6	45,3
26.5.2013	1,2	2,01	2,4	6,2	15,3	94,8	3,6	14,3	51,5	13085	88,6	44,8
27.5.2013	0,9	2,01	1,9	6,2	15,3	95,1	3,4	14,3	48,6	12814	88,6	43,9
28.5.2013	1,2	12,9	15,5	6,2	15,2	93,9	2,9	14,0	40,6	13262	88,2	45,2
29.5.2013	1,2	12,9	15,5	6,2	15,0	93,1	3,2	14,0	44,8	13557	88,2	46,2
30.5.2013	0,6	12,9	8,0	6,2	15,8	98,2	4	14,0	56,0	14345	88,2	48,9
31.5.2013	0,6	12,9	7,7	6,3	14,6	91,7	4	15,1	60,2	14116	88,2	48,1
Calorimetric Heat Value (dry)			15,3	MJ/kg					Total Mass Flow		393360	kg
Lower Heat Value			14,24	MJ/kg					Total Energy		1331	Mwh